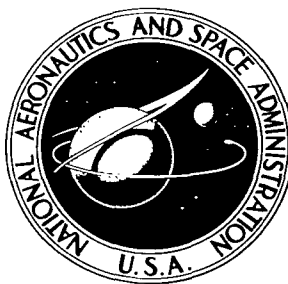


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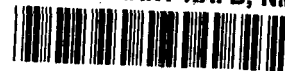
A DETECTOR-ANALYZER FOR STUDYING THE INTERPLANETARY PLASMA

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SUMMARY

The energy distributions of protons and other species of ions in interplanetary space as well as at satellite altitudes will be studied by using a new detection technique. Observations will be made as a function of time, direction, and position, over an energy range of at least 10 ev to 10 kev, with a maximum sensitivity of 10^{-18} A and with the capability of detecting single ions. Previous studies of the "solar wind" suggest many important measurements of its state, its interactions with planets, and its wave phenomena. The present instrument, $10 \times 30 \times 20$ (cm³) in size, contains an electrostatic energy analyzer, a secondary-electron-scintillation detector, high voltage supplies, and signal conditioning circuits. Laboratory work demonstrates constant response for protons having energies from 30 ev to 3 kev and a minimum detectable current corresponding to about ten particles per second. Progress is reported on the development of a velocity selector for separating ionic species. Hopefully this will lead to the solution of an important problem in solar wind studies, the determination of the relative abundances of protons and alpha particles.

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(Manuscript Received July 23, 1963)

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INTRODUCTION

Ample evidence now exists for significant particle and energy density in what used to be thought of as "empty space" in the solar system. Even during quiet periods the solar atmosphere extends to the earth's orbit and beyond in the form of a tenuous, streaming plasma having roughly these properties: a number density of 20 per cm^3 , a mean velocity of 5×10^7 cm/sec, a temperature between 10^5 and 10^6 °K. This "solar wind" was first proposed by Biermann (References 1-3) and was the subject of subsequent calculations by Parker (References 4-6). Satellite observations by Gringauz, et al., Bridge, et al., and Neugebauer and Snyder (References 7-11) confirm the existence of such a plasma outside the earth's magnetosphere, and as far away from the earth as the orbit of Venus.

Many properties of the solar wind are not well defined. A satellite instrument is now being developed to study some of them, such as the flow-direction and temperature of the plasma. The ionic composition of the solar wind will also be studied for the first time. Because of high sensitivity, it should be possible to scan the particle energy distributions at various angles with respect to the satellite-sun line and thereby search for anisotropies such as different temperatures parallel and perpendicular to the interplanetary magnetic field. Nonthermal distributions and large changes in plasma composition may be observed following the passage of magnetic storm-fronts.

Previous experiments have enabled some inferences to be made on these subjects, but the evidence is still incomplete in many respects. This shows the difficulties inherent in (and in many cases peculiar to) spaceprobe experimentation. The experimenter must strike a balance between the exhaustive measurements he wants to make and the capacity of the vehicle's telemetry system. Such a system can impart information only so rapidly, particularly when several experiments go on simultaneously. On long distance flights, such as the Mariner trajectory, information can only be transmitted at a rate of a few bits per second. There are weight and power limitations upon the

extent to which data can be stored and processed on-board. Several years of successively refined experimentation will be necessary before such complex objects as the interplanetary plasma become well understood. The present work is a step along the way; extensions of the instrument for future work are also being developed.

PRINCIPLES OF THE PLASMA ANALYZER AND DETECTOR

The analyzer-detector is actually a low energy ion detector, in which mass and energy discrimination are combined to give differential energy spectra for ions with a given value of m/Z . None of the individual components are original in concept; rather it represents the combination of them into a system which has advantages for operation in space.

Figure 1 is a diagram of the system. The ions enter through the slit and are selected differentially in terms of energy per unit charge by the electrostatic analyzer. The analyzer's acceptance cone can be varied over wide limits from say ± 1 to ± 20 degrees. Energy resolution can be varied from a low value to approximately 15 percent. The 127 degree deflection configuration is used (References 12 and 13) even though we do not need resolution better than 10 percent at present, both so that the resolution can be increased at any time, and also because it gives a convenient physical arrangement. Equal negative and positive potentials V are applied to these plates, and they can either be stepped or driven slowly through a range. In round numbers, not allowing for fringing effects,

$$\frac{E}{Z} = \frac{R}{d} \times V,$$

to the first order in d/R , where R is the plate radius and d is the plate separation. The maximum usable value of R/d is of the order of 10. At the same time V/d must be kept below about 10^4 in

order to avoid certain problems connected with field emission. Thus the maximum practicable value of proton energy which can be measured by this method is approximately 100 kev, a few times greater than the minimum energy which can be detected by a conventional scintillation counter. The two methods are therefore complementary.

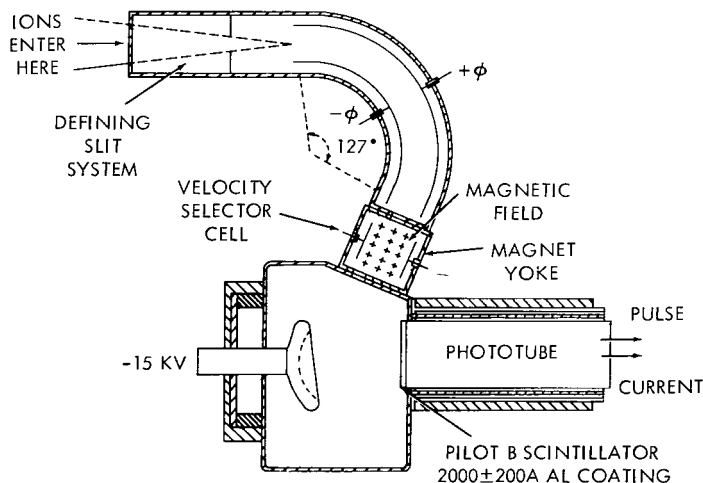


Figure 1—The energy-per-unit-charge and mass analysis instrument. The velocity selector is inserted between the analyzer and the detector box.

Figure 2 shows the result of the analysis of approximately monoenergetic beams of protons. The extractor potential of the ion source is shown for each curve, and it will be seen that the resolution of the analyzer is close to the predicted value. The arrows on the abscissa show the potentials which should be required to detect protons with the nominal potentials shown. The

differences between the positions of these arrows and the positions of the peaks of current represent the usual difference between the extraction potential of the ion source and the energy of the resulting ions.

After leaving the analyzer the ions enter a conventional velocity selector of the $E \times B$ type. The potential applied to the electrostatic deflection plates in this device is fixed for a given m/Z and magnetic field B . In the space application the magnetic field is kept fixed and the deflection cell must be surrounded by a well-designed yoke to prevent stray fields from interfering with other experiments on the same satellite. An example of the program of potentials applied to the various electrodes in a specific experiment is given below.

The ions, now belonging to a few species with fixed m/Z and energy, enter the detecting chamber where they are attracted to a high voltage electrode. This emission knob, made of highly polished aluminum, emits several (approximately 3) secondary electrons for each incident ion when maintained at -15 kv (Reference 14). These secondaries are accelerated by the same high potential and detected by a plastic scintillator-photomultiplier detector. The scintillator is covered by a thin (2000Å) film of Al which does the double duty of grounding the plastic and keeping visible light from the phototube.

Thus, for each incident ion, on the average 3 electrons are actually detected, each with 15 kev energy. These arrive at the scintillator in a time short compared with the resolving time of the output circuit of the tube. The detection efficiency for each 15 kev electron after it has passed through the Al film is of the order of 50 percent, and together these electrons give a pulse which is several times higher than the average dark current pulse of the tube. Assuming that 50 ev is required for each photon produced in the plastic scintillator and that 5 kev is lost in the Al layer, if the light collection efficiency is 50 percent and the quantum efficiency at the photocathode is 10 percent then we see that the average pulse contains

$$G \times \frac{10^4}{50 \times 2} \times 0.1 = 10 G \text{ electrons,}$$

where G is the gain of the tube. The efficiency of detecting at least 1 of 3 such electrons can be made greater than 80 percent. The detector thus counts single ions with a high efficiency. Such systems

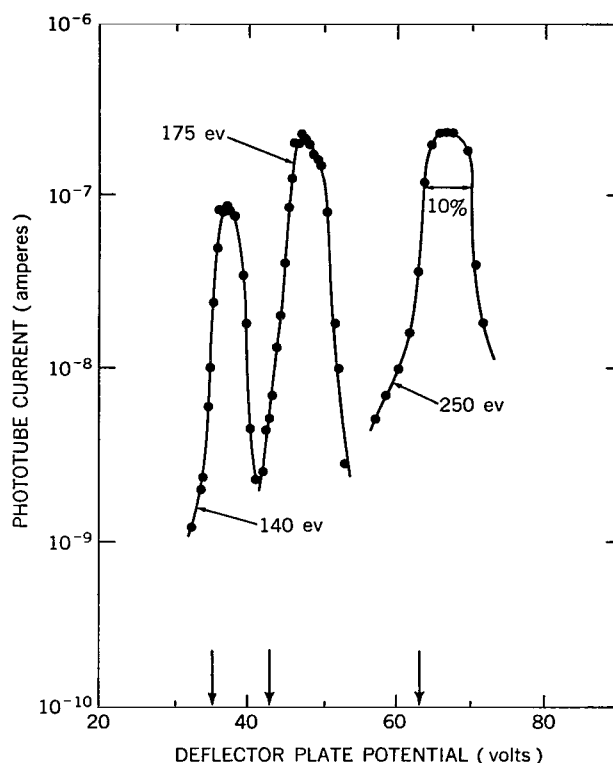


Figure 2—The result of analysis of approximately mono-energetic beams of protons. The figures attached to each curve show the extractor potential applied to the ion source. The deflector plate potential for selecting a proton of energy E is $E/4$ volts.

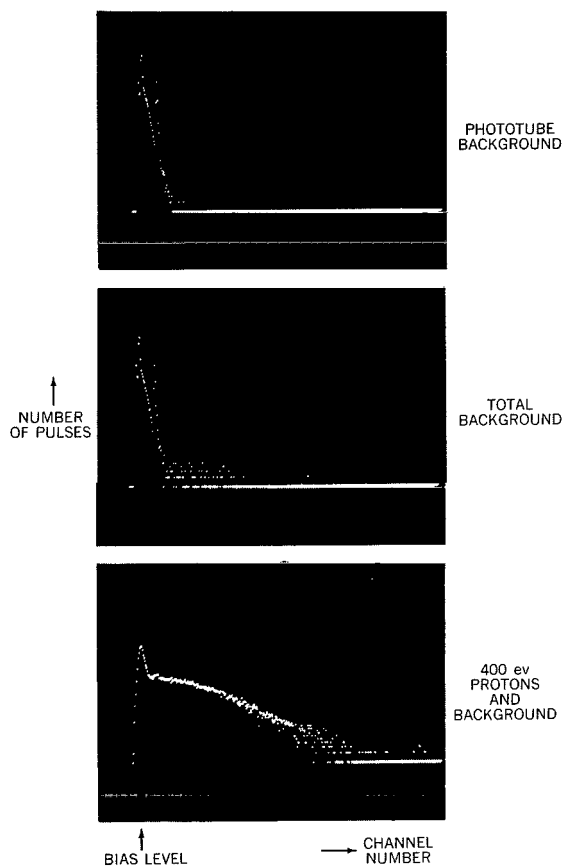


Figure 3—Pulse height analyses for the detector. The ordinate is logarithmic and the abscissa is 256 channels.

2. The third picture, which represents only 1/10 of the counting time of the first two, shows the position of the bias level which is set to reduce background. The lack of a distinct peak in the pulse height distribution is due to scattering in the coating covering the plastic scintillator. Although, as noted above, the average pulse at the cathode consists of approximately 10 photoelectrons, the spread is very wide.

Some refinements have been introduced in the analyzer-detector for space application. Figure 4 is a plot of ion and electron trajectories obtained by the conducting-paper technique (Reference 23) for motion in two dimensions. The electrode shape shown allows all ions over a wide range of incident energies to strike the knob and the resulting electrons to reach the scintillator. A direct check of this point has been made by measuring the current gain of the detector as a function of incident proton energy, and it was found to be constant from 30 ev to 3 kev.

In order to provide a very wide dynamic range of detectable current we proceed as follows. From 0 to 10^5 pulses per second the pulse-counting mode is used. For higher incident currents an

were independently developed by Schutze and Bernhard, Daly, and Afrosimov, et al. (References 15-19). Eubank and Wilkerson (Reference 20) have used the overall analysis and detection system for measuring plasma ion distributions in the laboratory, and Lincke and Wilkerson (Reference 21) have used the detector part alone for vacuum ultraviolet spectroscopy.

Figure 3 shows 3 pulse height analyses for the detector operating in the pulse mode. The ordinate scale is logarithmic and the abscissa represents 256 channels. Note two important points:

1. One of the difficulties encountered is reducing the background counting rate in the absence of ions entering the slit. The rate to be expected due to cosmic rays is of the order of 5 per second, but to realize this in practice requires extreme care. The surfaces of the high voltage electrode and the interior of the detecting chamber must be free from dust, since field emission from points can take place when the average field is of the order of 10^4 v/cm (Reference 22). If field emission occurs it makes itself felt by the presence of a number of pulses at least as large as pulses due to ions. These are seen in the second picture.

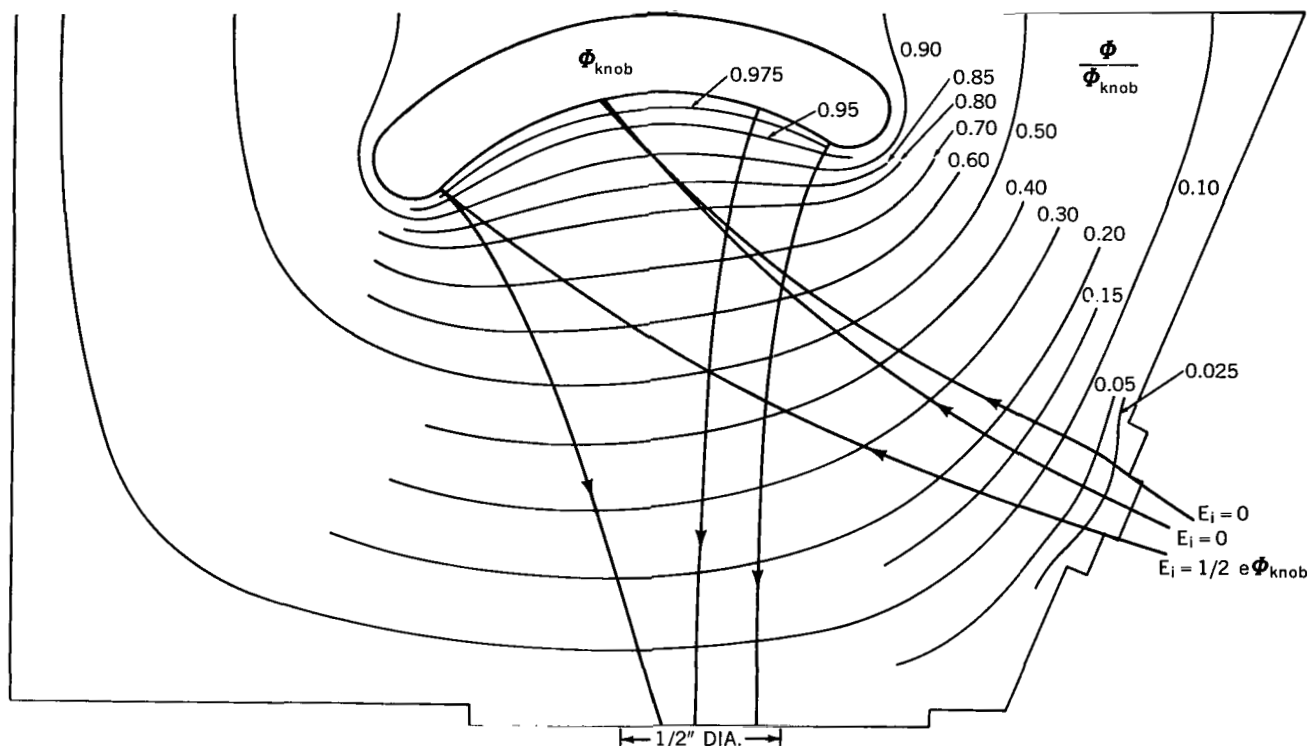


Figure 4—Equipotentials and trajectories for ions and electrons.

electrometer is connected to measure the current from the eighth dynode of the phototube. The dark current to this electrode is of the order of $3 \times 10^{-10} \text{A}$, and with an overall gain of the order of 10^5 some overlap exists between the two modes of operation. The maximum current which can be recorded in this way is approximately 10^{-4}A , corresponding to an input current of 10^{-9}A . Such a wide range is necessary for studying relative abundances in the solar plasma.

Figures 5 and 6 show photographs of a prototype of this device which was flown on an Argo D-4 rocket, NASA 8-18, to an altitude of about 1000 km from Wallops Island, Virginia, on September 28, 1963, with the intention both to test its characteristics for space flight and to obtain some information about the ionic constituents of the upper atmosphere (Reference 24). During flight the high voltage (15 kv) was turned on 10 sec after ejection of the nosecone. This turned out to be too short a time and glow discharge occurred in the detector box. This effect is partially due to outgassing of other parts of the payload, and will be avoided in subsequent flights by the provision of a large pipe between the detector box and analyzer, leading outside the payload. This unfortunate circumstance prevented us from getting any useful geophysical data, but evidence from telemetry indicates that all parts of the instrument otherwise functioned perfectly.

For this flight, only energy per unit charge was selected, ten steps between 2 and 1000 ev being provided. The various parts of the apparatus are indicated in Figure 5. Figure 6 shows a partially assembled view of the detector system, which weighs 7.4 lb when complete and consumes approximately

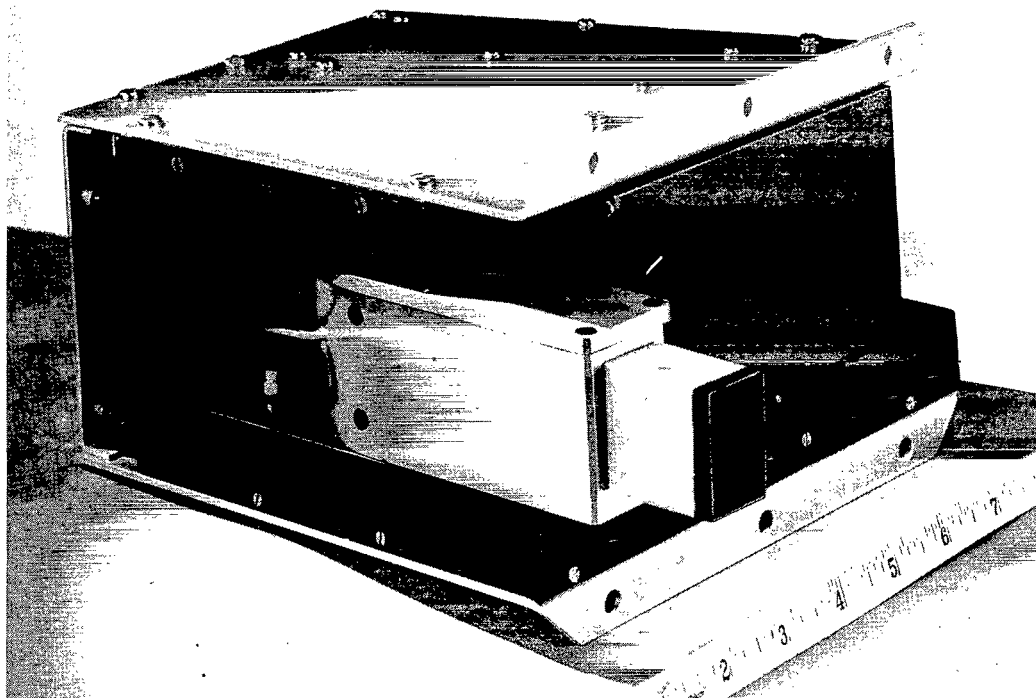


Figure 5—Prototype energy-per-unit-charge analyzer for the rocket flight test.

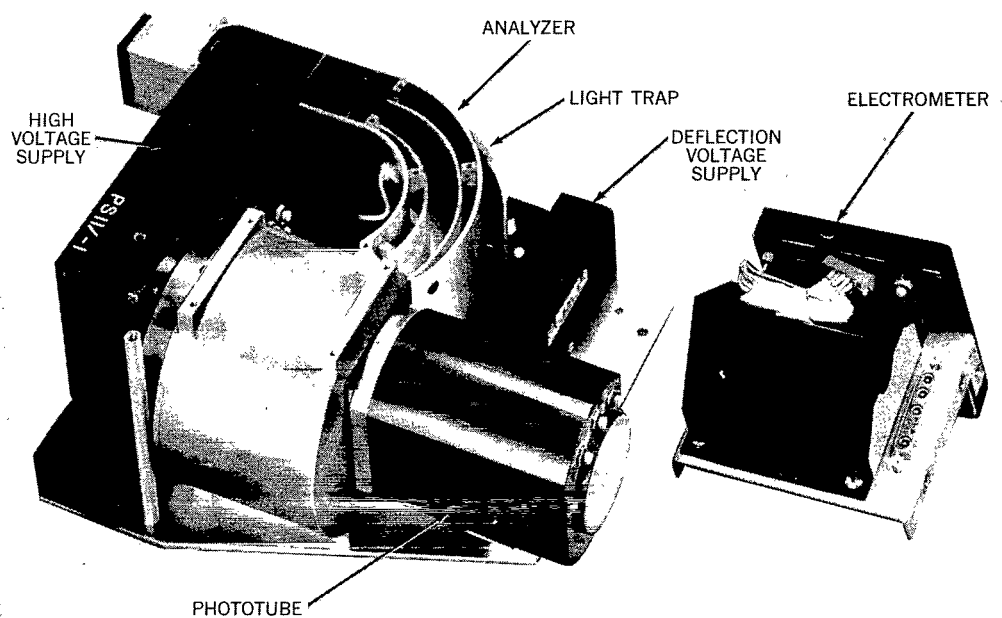


Figure 6—Partially assembled view of the rocket instrument.

1-1/2 watt at 28 volts dc. For satellite use the weight must be reduced, but this should not present an insuperable problem.

The solar plasma comes almost radially from the sun (Reference 10) and thus we are interested in counting ions when the entrance angle of the detector includes the radius vector between the sun and the satellite. Neither visible light nor ultraviolet radiation should produce counts. This problem has not been completely solved, but some precautions are shown in Figure 6. Visible light presents a great difficulty because of the very great flux of visible photons. Thus, as much as possible of the visible light must be prevented from entering the detection chamber, and that which does enter must then be prevented from entering the phototube. The thickness of the Al layer on the scintillator is fixed, since 5 kev is the maximum acceptable mean energy loss for electrons passing through it. The purpose of the horn-type light absorber (Reference 25) is to prevent light passing through the metal gauze window in the outer plate from re-entering the box around the analyzer. The principle variable is the degree to which light scattered from the metal gauze can penetrate to the box. Undesirable effects due to visible light can be prevented, but work in progress has shown that the counting rate due to the sun's ultraviolet radiation may limit the minimum detectable intensity of ions when the device looks directly at the sun. This limitation has been estimated to be about 1 order of magnitude above the normal background, which under the most pessimistic assumptions is about 100 counts per sec. Thus the background when facing away from the sun is about 100 sec^{-1} , and when facing the sun about 1000 sec^{-1} . There is considerable difficulty in determining the effect of solar ultraviolet radiation since the most usual and easily set up sources are monochromatic and are difficult to calibrate in absolute terms.

The development and testing of the detector has been carried out using a vacuum system with an RF ion source. By introducing hydrogen through a palladium leak, a beam consisting principally of protons is produced. By separating the detector a distance of the order of 1-2 meters from the source a uniform beam of particles may be obtained which is large enough to fill the slit of the analyzer. Current measurements are carried out using Faraday cups, and current division can be carried out to a fair degree of accuracy by such cups with a small hole in the bottom, if stops are introduced at the correct places in the ion beam. By substituting

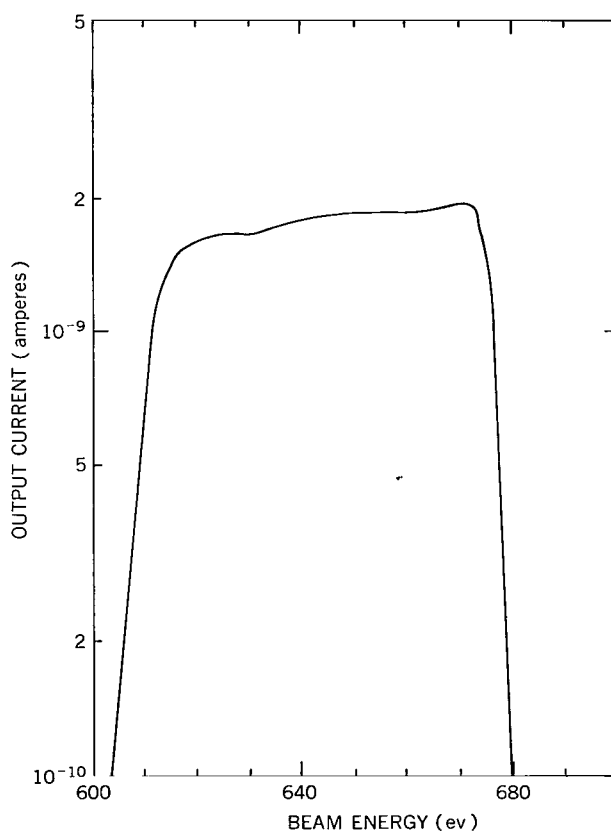


Figure 7—The energy profile of the analyzer, measured by using electrons.

suitable guns for the ion source, it is possible to use electrons for which the energy is accurately known. These were used to obtain the energy profile shown in Figure 7 for the energy-per-unit-charge analyzer. The detector is mounted inside the vacuum on a system of motor-driven tables, allowing both rotation about the axis of the defining slit and translation across the beam axis. This is used to check the solid angle of acceptance of the system, at present approximately 6×6 degrees.

A SPECIFIC SATELLITE EXPERIMENT

For the first experiments it is proposed to select $m/z = 1$ and $m/z = 2$, for a range of E/z . It is important to choose the values of E/z and the resolution in such a way that a peak in the spectrum of the solar plasma is unlikely to fall between values. As an example of this suppose the resolution chosen is ± 15 percent. Then a suitable set of center values of E/z is given below:

E/z for protons

0, 300, 450, 600, 850, 1200, 1700, 2400.

These values and the resolution obtained are shown in Figure 8.

There are two classes of satellites, those which are spin stabilized and those in which a surface or surfaces face fixed directions. The latter usually incorporate a surface oriented toward the sun, on which the instrument can be mounted. The values of E/z and m/z are then stepped through

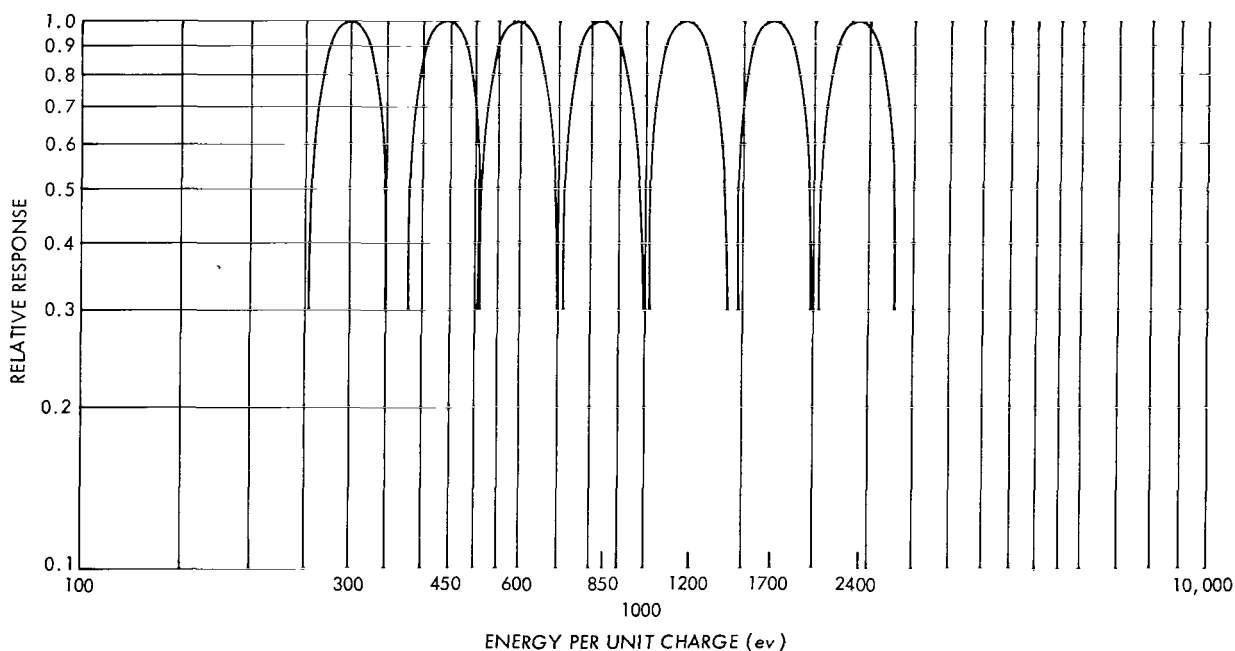


Figure 8—This figure shows the relative response of an analyzer having 15 percent resolution for the choice of values given here.

cyclically. For a spinning satellite, however, the acceptance cone of the instrument sweeps through the solar direction, and the signal becomes a pulse lasting for a time of the order of 0.1 sec. The response time of the electrometer must thus be short compared with this, and the category of E/z and m/z must be changed in synchronism with the rotation of the vehicle.

Clearly, high resolution will someday be required in view of the many constituents likely to be present in the interplanetary plasma. The work of Nier illustrates the developments in this field (Reference 26). The presently proposed lower resolution experiment is considered a necessary first step to assess the degree to which the mass spectrum may vary with the range of particle energy considered.

OTHER EXPERIMENTS

Apart from the sounding rocket and satellite measurements discussed, many other experiments are possible with this apparatus, depending on the satellite orbit. The most important appears to be the study of the structure of the sun-ward boundary between the earth's magnetic field and the solar wind. A satellite such as the Eccentric Orbiting Geophysical Observatory (EGO) would be appropriate for this study since its orbit is designed for repetitive transits into and out of the magnetosphere.

Orbits of greater eccentricity than that of the EGO may provide an opportunity for study of the "standing shock" which some theoreticians believe to be the result of interaction between gas reflected from the magnetosphere and the incoming solar wind (Reference 27). By picking out the proton component, for example, and recording energy distributions as a function of position and angle, we would find density and temperature profiles in the plasma over some depth in the interface region.

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